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Development of Organic Rankine Cycle for Microcogeneration by using Scroll Compressor

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Abstract— **ORCs are being used in low grade heat recovery applications. The Model prepared is a 1 kW ORC comprising of four main parts: evaporator, Scroll expander, condenser and feed pump. Main restriction, while designing ORC model, was to choose working fluid. Working fluid will be a refrigerant whose properties will be modified to the working conditions in which the heat recovery is carried out. A refrigerant R134a (a gas used for Household refrigeration system) has been selected as working media due to its required performance, high safety and frequent availability in Pakistan. An investigational study has been carried out on an ORC, recovering heat from hot water at a temperature ranging from 130-140°C. The scroll compressor will be used in reverse as a volumetric scroll expander to extract work from the system. Physical Model of every equipment of the test bench has been validated. The ORC test bench has been commissioned and testing has been performed under different working conditions to understand its behavior broadly. In the last section of this work, future work has been proposed for better optimization of the ORC test bench.**

Index Terms— Organic Rankine Cycle, Scroll Compressor, Microgeneration, Development of System, Power Generation.

I. INTRODUCTION

A survey had been conducted by World Energy Council in 2015 which shows that the most important need of the hour globally is to devise ways and methods for increasing energy efficiency and utilizing renewable energy resources (1). The ever increasing thirst for energy for industrialized and under developing countries alike are driving the need for action. Waste heat recovery (WHR) systems can be part of the solution for increasing energy efficiency and generating renewable power. A key technology used to generate power from heat is the conventional steam Rankine cycle (RC) which is used where high temperature (>340 °C) heat is available (2). Unfortunately, not all heat sources produce sufficiently high temperature heat required to drive a conventional steam Rankine cycle.

The development of lower boiling point organic working fluids has provided an avenue for increased applications of RCs to heat sources at relatively lower temperature. Organic Rankine cycles (ORC), work with fluids that are organic in nature instead of water, and utilize heat at temperatures around 65 °C. Sources of heat for ORCs may be either waste sources or dedicated sources.

The technologies to build ORC systems were available as early as 1976. The economics of ORCs weren't favorable until the use of modified off the shelf refrigeration components and there are still technological and economic challenges to wide acceptance of the ORC technology to smaller applications in the less than 100 kW range. Smaller systems are important as there are many more sources of waste heat in this range of operation. To that end, the effort in this work was undertaken to create an environment to conduct research on sub-100 kW ORCs and collect preliminary results for the configuration of working fluid and expander. Section II describes the working principal of Organic Rankin Cycle (ORC) and summarizes the key points in waste heat recovery by means of ORC.

II. HOW ORGANIC RANKINE CYCLE WORKS

The Organic Rankine Cycle (ORC) as compared to conventional Rankine Cycle can work at very low temperatures, thanks to the organic fluids with low boiling points. Although the efficiency of an ORC is typically between 10% and 20%, yet the properties of the organic fluid has a great impact on the overall performance of ORC cycle.

The working process (as shown in Fig. 1) is completed in four (or five) consecutive steps:

- An organic fluid that is in liquid state at relatively low pressure, gains pressure by using a feed pump.
- This fluid under high pressure will be vaporized by a heat source. The superheated vapor will be expanded trough a turbine.
- An optional regenerator can be added between expander exhaust and condenser supply. This results in heat exchange between the two streams (inlet to evaporator and exit from expander) of working fluid which contributes towards overall efficiency of ORC.
- The working fluid will be condensed and flows back to the feed pump supply.

The working code/principal of an ORC is thus alike to the conventional Rankine cycle with working fluid as water. The main difference between the two cycles is the choice of working fluids; ORC utilizes organic working fluids which have low boiling points, thus making it possible to operate the cycle at relatively low temperatures.

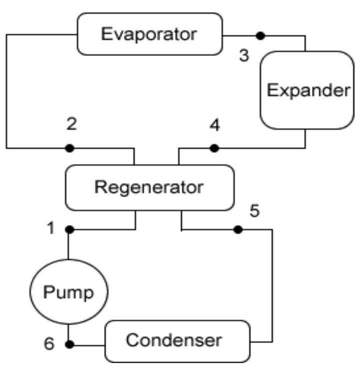

FIGURE 1. Components of an organic Rankine cycle

The main objective of this research work is to model an efficient useful application based on Organic Rankine Cycle by finding possibilities of design amendments for minimizing the cost and enhancing the efficiency. The experimental model of ORC has been developed with low cost and operational results have been obtained accordingly. This is an attempt to introduce ORCs in Pakistan which is an advance concept of power generation as compared to conventional Rankine Cycle, so that it may contribute towards meeting the growing energy demands in future.

III. Principal Steps in Modeling of ORC Cycle

The prime portion of the in hand research work is devoted to the finding out the best suitable application(s) for heat recovery, with their pros and cons, deficiencies, and potential usages. A comparison is performed among several working fluids to find the best suitable & environment friendly ones. As the expander/scroll compressor has a vital significance, so a reasonable portion of the thesis/research work is devoted to its study.

Scroll compressors have a lot of advantages over the conventional reciprocating compressor. They have less moving parts which tends to have higher reliability. The gas flow is often constant which leads to lower noise. Also there are no inlet and outlet valves which may contribute towards producing noise. Scroll compressor also generate low vibrations as compared to reciprocating compressor which is an important factor for the reliability of our experimental model. The working model is then explained, with detailed summary of each component and its measurement devices. The experimental procedure is elucidated with all the practical obstructions and the suggested remedies.

Thorough analysis of the measurements has been put forwarded, in order to enlighten the difficulties perceived in the test(s).

IV. Literature Review

Organic working fluids have been developed which have high molecular weight and specific heat, that has low ozone depletion potential called ODP as well as low global warming potential called GWP and low flammability. Extensive researches have already been carried out on the effect of working fluid selection as it applies to Rankine cycles [1-7]. Working fluids studied include water, ammonia, chlorofluorocarbons, hydro fluorocarbons, hydro chlorofluorocarbons, carbon dioxide and lot of other organic materials. Plenty of working fluids have too much attractive thermo physical properties, but are quickly ruled as unfavorable due to certain reasons like flammability, toxicity, lack of availability, cost factor, requirement of high working pressures and reason of phasing-out due to environmental considerations.

Efficiency of an ORC system mainly depends on the efficiency of expander [8,9]. Selecting expander for specific operating temperatures, expansion ratio and working fluid is very much important. Generally, expanders are of two types: turbo expanders as well as positive displacement (PD) expander. Former type is mostly used in large scale power plants while PD machines are used in smaller power plants. Turbo expanders can attain the rotating speeds as much high as 50,000 RPM and have performance efficiencies range up to 60 to 90%

Positive displacement machines operate at slower speeds and exhibit higher expansion ratios than turbo expanders of same size. The slower speed eliminate the need of higher cost rotating components and decrease the manufacturing costs in areas such as balancing. Due to these factors cost of expander for PD machines is less as compared to turbo expanders. PD expanders have lower peak efficiencies than turbo expanders, but work well through a range of operating conditions. As concluded by Badr et el. [10], PD expanders are best choice for small waste heat systems.

The expression “waste heat recovery” basically expresses the factor of utilization of any sort of heat rejected to the environment. Viable heat sources are numerous in breadth and number of installations. Examples include industrial processes, exhaust from gas turbines, IC engines, and return flows from steam boilers and furnaces etc [11]. A thorough review of applications of industrial waste heat recovery is provided by Johnson and Choate [12]. Waste heat can be converted to electricity using a thermodynamic cycle by exchanging the heat directly to working fluids.

Organic Rankine cycles produce electricity /power from various heat sources with low temperature range like geothermal, biomass and from solar concentrators [13–16]. ORC technology is being used by companies such as Ormat, Turboden, General Electric, Pratt and Whitney, Koehler-Ziegler, Infinity Turbine, Electratherm, GMK, Adoratec [17, 18]. Sizes of Organic Rankine cycle application are in range from under 1 kW [19], to multi-unit applications producing several megawatts [20]

V. Experimental Procedures

Working fluid chosen for the present test bench is R-134a. The source of heat is comprised of hot air/saturated steam flowing at temperature range from 130-140 C0 with pressure at 6 bars from a already installed boiler in Heat & IC Engine Laboratory at University of Lahore. The expander selected is an scroll compressor of HONDA Car which is modified to be run in expander mode. Speed (RPM) of expander will be measured by means of tachometer. The condenser is fed with tap water for cooling of refrigerant gas after passing through the expander in direct cooling method whereas in indirect cooling method a separate radiator has been used wherein working fluid is further cooled by using small 12 V Fan.

For measurements of pressures and temperature of the cycle at different states pressure gauges and Thermometers and pressure transducers have been used at certain specific points on piping system. Figure 2 gives the overall schematic view of the test bench designed for development of organic Rankine cycle for micro cogeneration by using scroll compressor.

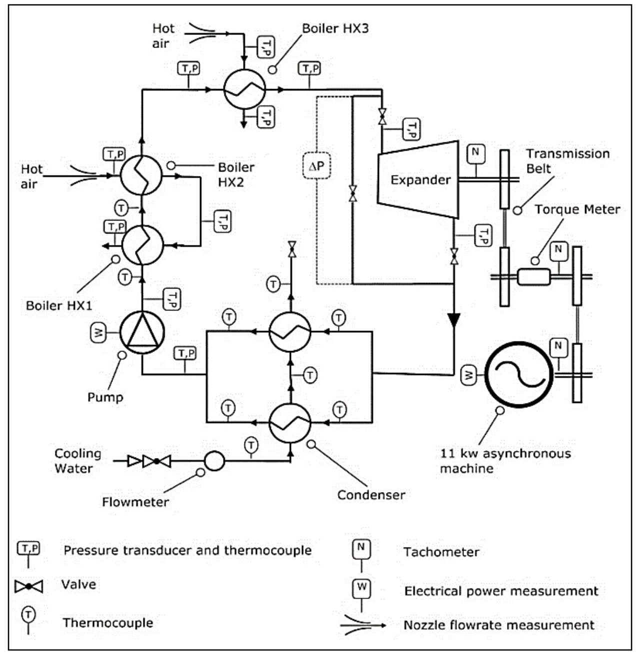

FIGURE 2. Schematic View of the Rankine Cycle test bench

During commissioning of ORC test bench three variables are of main interest whereas rest of all to be held constants, but in actual it was not so easy to do this. During commissioning/testing of ORC test bench variations in flow rate of organic fluid and water temperature at the entry point of condenser were observed.

FIGURE 3. ORC Test Bench.

Before starting the commissioning of ORC test Bench all the valves were actuated in open Positions as shown in ORC Test Bench Single Line Diagram. The positions of all the valve are adjusted so that from the heat source it directs the entire mass flow rate of water /steam through evaporator of ORC test bench during testing.

The condenser temperature was tried to controller as low as possible by putting ice in the bucket and in addition fan of radiator condenser was also put in operation to maintain the temperature of working fluid at 25 °C. During testing, it was visually noted how long fan of radiator was on duty during any data collection point so that overall system efficiency calculations could be made. Particulars of the boiler are tabled below:

TABLE 1.
PARTICULARS OF BOILER

Status of Boiler:	Functional
Fuel Use:	Natural /Sui Gas (Connection is available)
Operation Time:	04 Hours
Safety Certificates:	Already get from the supplier and additional Pressure Relief Valves are available and Functional and shutdown automatically in case of emergency.
Maximum Pressure achievable	80 Psi Almost 6 Bar
Maximum Temperature of Steam achievable	130-140 C0

VI. RESULTS AND DISCUSSION

During commissioning of the ORC test bench a lot of difficulties were faced in the form of leakage of organic fluid or working fluid through seals of pump, variable temperature of the cooling water at entry point of condensers etc however only one test day was successful in running a turbine /scroll expander.

After doing the successful commissioning of the test bench, boiler was operated to get the steam with temperature 100 C0 at 06 bars. With the aforementioned improved quality of the steam passed through the evaporator. It was noted that purity of the organic fluid at the exit of evaporator as well as entry point of scroll expander was quite improved and eventually speed of the expander/turbine was improved which was measured by the tachometer.

Rotational Speed of Scroll expander/ turbine was reached up to approximately 300 RPM only due to reduced/controlled flow rate and mixed quality of the working medium. The turbine could not spin fast enough to run “where it wanted to” with a 1:1 turbine to generator belt ratio without risking damage to the generator. Leakage through the seals of pump would not let the pump develop the differential pressure required to operate at the designed pressures. To counter the issue (1) above, operating conditions of boiler were improved by increasing the temperature and pressure of the steam to be passed through evaporator. Issue (2) from above was solved by replacing the Positive displacement pump by small compressor/pump of the air conditioner so that the pump can be capable of producing differential pressure of at least 10 bars.

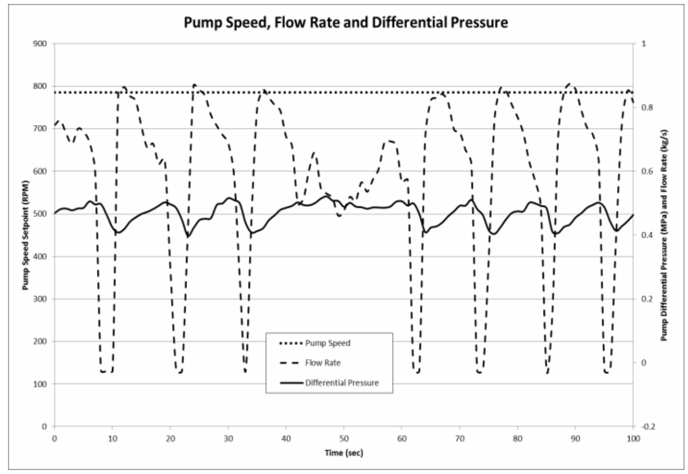

Figure 4. Pump Speed, Flow Rate and Differential Pressure. Note differential pressure peaking at 0.5 MPa and flow rate dropping repeatedly while pump speed is constant. This indicates the pressure relief valve was opening repeatedly.

After doing the trial test of the test bench on November 05 2018, boiler was operated to get the steam with temperature 140 C0 at 08 bars. With the aforementioned improved quality of the steam passed through the evaporator. It was noted that quality of the working fluid at the exit of evaporator and entry point of scroll expander was quite improved and eventually speed of the expander/turbine was improved which was measured by the tachometer.

Following results were observed after experimental analysis:

- Leakage of working fluid R134a was removed and pump was producing required differential pressure of at least 08 bars.
- Rotational Speed of Scroll expander/ turbine was reached up to approximately 800 RPM
- The Working fluid R134 inlet temperature to the evaporator was not stable during testing.
- It was shown the exit pressure at the condenser was within 0.007 MPa of the inlet to the pump.
- A system relative efficiency to turbine RPM plot was obtained.

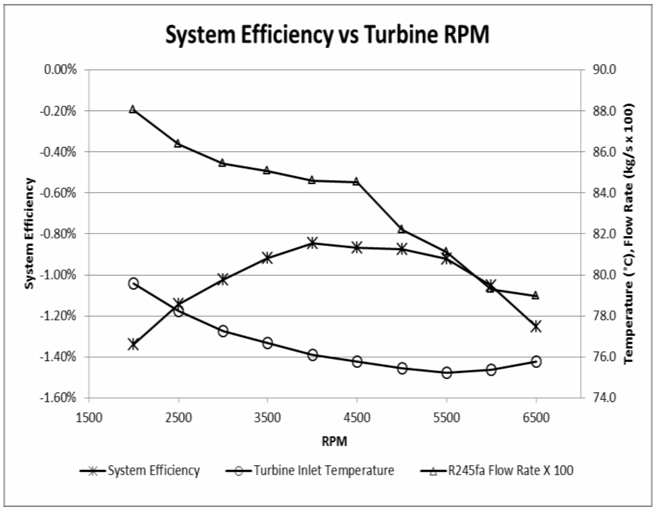

Figure 5. System efficiency versus turbine RPM.

Based upon the above mentioned results of experimental setup of ORC, it can be said that the ORC test bench model is operational and can be used to carry out further experiments. There were some errors in the beginning which were removed. All the components and overall model possess great potential for learning and this can be an initial attempt to introduce the advance energy-efficient concept of ORC in Pakistan.

VII. CONCLUSIONS

ORCs can be a great avenue towards energy contribution for countries like Pakistan. This study shows that how ORC models can be developed within the country that are fully operational, as concluded by the operational results carried out by ORC test bench. This experimental setup has been developed and operated within Pakistan and no component or device was imported for this purpose. This indicates a great possibility that such advance technologies can be employed and implemented indigenously, only the necessary awareness is required. Thus it can promise a great potential for future concerns.

Due to a lack of required testing facilities during this work, it is recommended that additional data be taken from the SANDEN manufacturer of the scroll expander. Sanden's next generation scroll compressors is designed to accomplish exceptional robustness. The scroll compression mechanism provides smooth, silent operation and high efficiency. It has swept volume of 77.1 cm3. It has shown great potential as a robust expander for tests on steam. The preliminary results from this work while operating the turbine on an organic fluid are promising. The turbine should be completely characterized through a realistic range of inlet and outlet conditions and rotational speeds.

Power meters need to be installed on the feed pump, generator and condenser to do the accurate system efficiency calculations. Also, a torque senor should be installed on the turbine to allow calculation of actual turbine power output without including belt drive and power conversion losses.

One of the overarching goals for the test bed is to conduct research on different expanders and working fluids while working at varying condenser conditions. Especially interesting would be to study the performance of variable displacement expanders with varying condenser temperatures and pressures.

A final recommendation for future work on the ORC test bench is to arrange a low RPM generator which can be connected to scroll expander to produce electricity. The low RPM generator can be easily available from local market of Pakistan. After connecting the aforementioned low RPM generator ORC efficiency test bench can be slightly improved by modifying the different equipment of test bench.

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